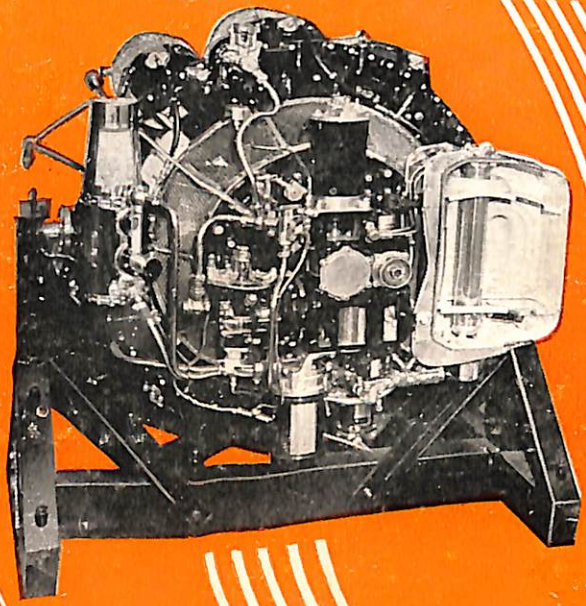
GAS TURBINES & JET PROPULSION

AN OUTLINE OF THE PRINCIPLES INVOLVED IN THE NEW THERMAL JET SYSTEM OF AIRCRAFT PROPULSION



Incorporating: Centrifugal Compressor • Axial Flow Compressor Rocket and Jet Propulsion • Essentials of a Gas Turbine, etc.

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An outline of the principles involved in the new thermal jet system of aircraft propulsion.

by

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Preface

To understand is to re-invent external realities within one's own mind.

Original inventors have often derived inspiration from some simple, everyday phenomenon which remains almost unobserved, and certainly accepted without interest, by the general run of men. One such instance is Watt's observation of the kettle lid being raised by the pressure of the steam within; by proceeding, logical step to logical conclusion, he invented the steam engine, first by arriving at conclusions in the realm of pure theory and later by application of these conclusions to practical purposes, so that observation of a simple phenomenon developed into a high'y complicated application of the principle involved.

We therefore make no apology for treating the present subject in its initial stages in an elementary manner, in the conviction that only thus can the logical progression from inspiration, through pure and applied theory to final practical realization, be fully appreciated and the reader be in a position to "re-invent" the existing external reality.

Let us further state that even the most sensational, epoch-making inventions are merely the application of a combination of immutable natural laws which have operated since the beginning of time, manifesting themselves in simple, everyday phenomena to all who care to observe.

So in the case of the Gas turbine. Who has not seen those rotating lampshades so common in the days when shop windows were illuminated? Or the spinning cowl on top of a chimney pot? Or those slowly turning masks which impart to an electric fire the impression of flames and smoke? All these—and innumerable other applications of the natural law that gases expand under increased temperature—are in reality elementary turbines, or more particularly, hot air turbines.

Two self-evident, but commonly disregarded principles in dealing with complex problems were expounded to the writer by the late Mr. Henry Ford. One, that every large and complex problem can be broken down into a number of simple problems, and the second, that to banish a mystery it is only necessary to give it a name. In the following chapters both these considerations will be generously applied, and if, for purposes of convenience the name "Initial absolute pressure" or "Initial pressure at −275°C." (which is the same thing) can be abbreviated to "P," surely this produces no more mystery than the Dutch equivalent for their ponderous "Horseless-trackless-petrol-driven-carriage," which is simply an "auto."

One of the essential tools to enable us to re-invent is a knowledge of Mathematics, but just as the owner of a motor car seldom uses more than his wheel brace, tyre-levers, screwdriver and pliers, from the assortment supplied in his tool-kit, so we hope to be able to use only those almost universally known and applied processes of mathematics to deal with the subject.

CHAPTER I.

ESSENTIALS OF A GAS TURBINE.

Let us suppose that two electric fans are set face to face, one being driven by an electric motor and the other running free (see Fig. 1). Let us further suppose that both fans are connected by a cylindrical pipe. The result of starting the electric motor will be that fan A will suck in air which is thereby compressed and will propel it through fan B, which will be rotated by it. Now let us suppose that a combustion chamber C is introduced in the connecting pipe into which some liquid fuel is pumped through a nozzle and then ignited. The resultant expansion of this burning gas will serve two purposes: (1) to add to its quota of expanding *fluid* to the compressed air rotating fan B, thereby increasing the speed of fan B; and (2) to increase the temperature of the compressed air sucked in by fan A, which will have a similar result on fan B. The sum total of these additions to the propelling fluid will result in an attempt by fan B to rotate faster than fan A, which, however, is impossible owing to their common shaft, so that a certain amount of power will be generated in excess of requirements for this simple cycle. This excess of power, if increased, will finally relieve the electric motor driving fan A of all load, and, as the excess of power increases, will turn the motor into an electric generator producing useful power which can be applied to other purposes. Thus we have a self-contained unit which is producing power and can therefore be described as a *prime mover*.

But we have only traced our mixture of compressed air and the products of combustion in the combustion chamber as far as the outlet from fan B. Naturally, much of the kinetic energy used in turning fan B has been exhausted, but still the escaping mixture contains both expanding energy and heat. This can be exhausted into the ambient air and wasted, or it can be utilized to impart some of its heat to the incoming air

being sucked in by fan A, thus increasing the temperature of the mixture in the combustion chamber by giving the ignited liquid fuel less work to do. Such utilization of the exhaust heat is achieved by introducing a heat exchanger between the air compressor chamber and the combustion chamber. A further benefit of the heat exchanger is that whilst the exhaust gases heat up the air on the inlet side, the cold air on the inlet side also cools the exhaust gases by robbing them of that heat with consequent saving of the material of which the exhaust is constructed, which would otherwise quickly deteriorate by burning.

Here, then, we have a simple gas turbine composed of the following essentials :—

1. An air compressor (fan A).
2. A starting motor which later becomes a generator.
3. A heat exchanger through the inside of which pass the exhaust gases, and over the outside of which passes the compressed inlet air. (Not shown in the diagram).
4. A combustion chamber which receives
   a. the compressed and slightly heated air,
   b. the injected liquid fuel.
5. A means of ignition for starting up, say, a sparking plug, for once the combustion chamber has become hot it will itself ignite the fuel.
6. A gas turbine (fan B) rotated by the gaseous mixture from the combustion chamber.
7. An exhaust.

It will be seen that both the electric motor and the sparking plug are out of commission once the unit has attained a sufficient speed and temperature.

The predominant advantage of a gas turbine is the fact that it can operate at temperatures far in excess of those possible in other prime movers, and as heat is work, the benefit is obvious. For the turbine to operate the compressor without the aid of the starting motor would call for a combustion chamber temperature of the order of 700 °F., whilst to turn the starting motor into a generator would call for about 1,000 °F.

A INLET FAN (DRIVEN)
B DRIVER FAN
C COMBUSTION CHAMBER
D ELECTRIC STARTER, LATER, GENERATOR.

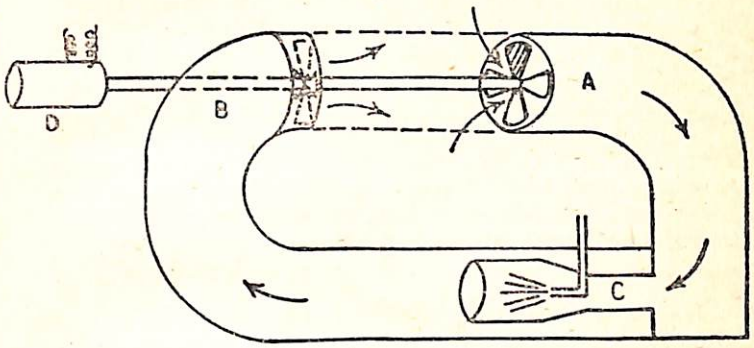
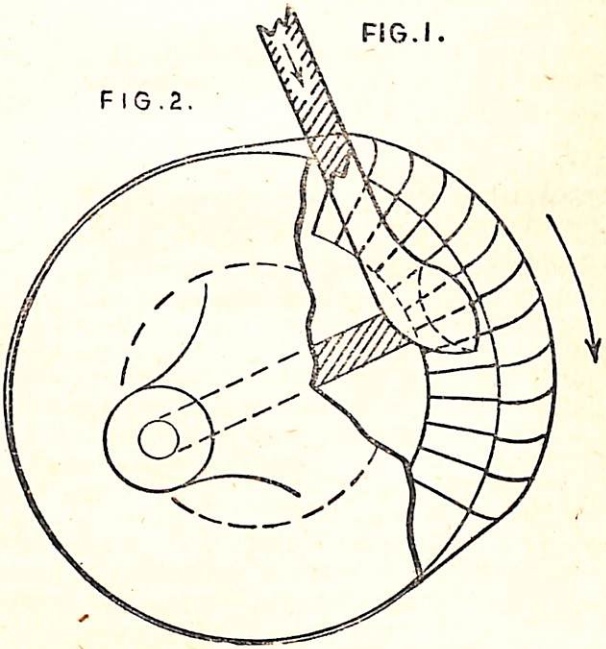


FIG. 1.

FIG. 2.



For jet propulsion of aeroplanes in which high fuel consumption and short life are not of paramount importance (as in the case of the jet propelled fighters of the R.A.F.) a temperature range of 1,500 to 1,800 is used, but for general commercial purposes, chiefly for turbo-electric locomotives and marine engines, the inlet temperature seldom exceeds 1,100°F. One of the chief difficulties in this respect is to find a non-burning or refractory metal combining the physical properties necessary to resist enormous stresses and strains with properties making it suitable for manufacture of turbine stators and rotors, and the ability to withstand high temperatures without distortion. Extensive research is at present being carried out in this field, and several improved refractory materials have already found practical application, but chemists and engineers will not be satisfied until materials withstanding 2,000°F. or more are available.

Having a general understanding of the principles involved and of the fundamental components of a simple gas turbine, we can now briefly review the development of the system, and since we are chiefly concerned with turbines for jet propulsion of aircraft, we can at once ignore a large range of units finding their application for other industrial purposes.

ROCKET PROPULSION AND JET PROPULSION.

There are primarily two different types of turbine characterised by the action of the expanding fluid so as to set up a motion in the machine, thus transmitting energy into a governable mechanical movement. These are known as the (1) Impulse turbine and (2) Reaction turbine. In the Impulse turbine, a jet of the high-velocity expanding fluid is directed into a series of cups connected to a central axis, about which they can rotate in the manner illustrated in Fig. 2. These cups are technically known as "buckets," and a term which we shall often meet in calculating efficiencies when referring to Impulse turbines is "tip speed," which obviously means the velocity of a point on the circumference of the circle of which the axis or shaft is the centre. The Reaction turbine, on the other hand, operates by the discharge of an expanding

fluid into the surrounding or *ambient* air (or even into a vacuum). This principle is similar to that of a Catherine wheel, in which the discharge of burning gunpowder causes the gases thereby released to spurt forth with ever-increasing expansion and hence ever-decreasing power and to give a rotating motion to the Catherine wheel.

A knowledge of the principles involved in both systems will be necessary, as the whole power unit used to propel aeroplanes, known as the thermo-dynamic system, and consisting of a compressor, a combustion chamber, a gas turbine and an injection nozzle, utilizes the characteristics of both types of turbine.

Now what is the difference between a jet propulsion system and a rocket propulsion system? Since both systems rely upon the discharge rearwards of a high-velocity jet of fluid, some scientists maintain that both systems should be classified under the same general principle, and whilst this is undoubtedly true, two very important practical considerations compel us to distinguish fundamentally between them. In the case of a rocket the propelling fluid is the result of a chemical *combination of two or more propellants* (*fuels contained within the rocket*) *producing a high-velocity rearward jet which operates quite independently of the surrounding fluid.* A jet propulsion system, on the other hand, *operates through the process of thermal transformation of the surrounding fluid so as to produce a high speed rearward jet of that surrounding fluid.*

As the surrounding fluid, through which terrestrial objects fly, is air, it follows that a rocket, which is independent of air, can be propelled either in air or in a vacuum. In fact, by rocket propulsion, optimum efficiency *is* achieved by the jet in a vacuum, hence the feasibility of inter-stellar travel by rocket propelled projectile.

In the case of jet propulsion, however, as the term is generally understood, the system is entirely dependent upon the air and therefore could not operate outside the earth's atmosphere.

Nevertheless, there is one point of similarity which we shall examine more technically at a later stage, namely, that

any jet of propelling fluid, be it air or any other combination of gases, gives its maximum propulsive efficiency in a vacuum.

The second practical consideration is that whereas a rocket must carry within itself the whole of its propellant fluid (usually in solid or liquid form), with consequent short range and high fuel consumption, the thermal-jet system is constantly refuelling itself with its principal propellant fluid (air) and carries only its subsidiary fuel (paraffin or some other liquid fuel), with consequent economy of initial weight and fuel consumption combined with longer range. Thus we feel justified in making the distinction and in adhering to the definition of jet propulsion given above.

CHAPTER II.

THE PHYSICS OF AIR.

In conformity with the intention expressed of unblushingly dealing with the subject in an elementary manner, certain conceptions can be best explained by analogy.

Latent and kinetic energy, velocity of air flow and outlet velocity, transformation of energy into velocity and vice versa, volume and pressure have all to be visualised if the later, more technical arguments are to be followed.

Imagine a helical spring ; as it lies upon the table it is a lifeless, inert piece of metal. Now compress it and then release it. The result is that it will exercise force, or use energy, or expand or move, back to its original inertness. In the action of pressing the spring two forces are acting upon it—1, the pressure from above, and 2, the resistance from below, and it is the sum of these two forces which impart to the spring its ability to return to its original shape and inertness. The sum of these two forces is known as energy, and this energy is stored in the spring until it is released. Thus, when the spring is compressed, it is capable of releasing the stored energy, which is known as latent energy, and when it is released the expenditure of that stored energy is known as kinetic energy. " Latent " comes from the Latin work " latens," meaning resting, and " kinetic " from a Greek word meaning moving. (Compare with Kinematograph, a moving picture). The same applies to fuels : a piece of coal is capable of giving out a certain amount of heat if burnt. This quantity of heat is called latent heat, as distinct from the kinetic heat which it sends out when burning.

Now suppose the compressed spring is released: it will expand either slowly or quickly according to whether it is released suddenly or gradually, and the speed of its release is

known as its velocity. But, again, suppose that the compressed spring is pushed along a tube without its pressure being released, the speed of its movement through the tube will still be a velocity. If again, the compressed spring is pushed through the tube and if at some point of its journey it is released, it will have two velocities—1, its own velocity (in the case of a gas called Mass flow), and 2, the velocity of movement within itself as it expands, due to the release of its kinetic energy.

Now let us again compress the spring and note that it has become smaller ; it has, in fact, undergone a reduction in volume so that the pressure exerted upon it has a direct influence on its volume.

Finally, it will be noted that when the spring has released all its energy, it resumes its former size. This property is known as elasticity. When it is said that a substance is perfectly elastic, it means, then, that it will resume the condition in which it was after the expenditure kinetically of the energy put into it. In other words, its input energy is equal to its output energy. Less elastic substances, of course, will give as output only a portion of the energy input. A glass marble bounced on a stone or glass floor will continue to bounce many times, but to an ever-decreasing height, simply because the energy expended to raise its weight to the original height from which it was dropped is only partially given out by it at each bounce. Not so with gases. The molecules of a gas are *perfectly elastic*, and the force known as pressure is caused by the molecules moving at great speed between the enclosing walls of its container. Once pressure has been applied to the gas, the molecules will " bounce " from one wall to another, but each time they will bounce back the whole way, and hence the pressure will never be reduced unless as a result of some outside influence, such as temperature drop, a leakage, etc.

It is hoped that this short elementary consideration of some basic physical laws will contribute to the understanding of the next chapters.

AIR AND ITS COMPRESSION.

In order to understand the essential functions of the thermal-jet propulsion system for aeroplanes, we must review the properties of the air, the phenomena occurring when it is subjected to change of temperature and pressure, its composition and the means for measuring and weighing it, together with the behaviour which may be expected of it under a given set of circumstances.

Air is a mixture of gases in mechanical combination. These gases consist predominantly of Oxygen, Nitrogen, Hydrogen and water vapour which is in itself a chemical combination of Oxygen and Hydrogen. Naturally there are innumerable other gases present in the atmosphere in more or less minor quantities, and to a great extent dependent upon the locality from which any particular sample of air is taken. But for our present purpose we may ignore these.

The molecules of the gases composing the atmosphere are in a state of constant movement, and by striking the walls of any enclosing vessel they produce *pressure*. Since these molecules are perfectly elastic they will continue to move and the pressure will be maintained. This pressure may be further augmented by increasing the *velocity* with which the molecules move, a condition which is achieved by *heating* the air. Thus, for practical purposes, we may say that PRESSURE increases with TEMPERATURE and vice versa.

But we must have a starting point or standard at which to commence any calculations, and the standard of pressure is taken as that of air at sea level and at 60° F. Under these conditions, the ordinary air which we breathe has a pressure of 14.7 lbs. on every square inch of surface on which it rests. The usual way of expressing this standard is written 14.7 lbs./sq. in., or more simply : 14.7 p.s.i. It is evident, then, that on the earth we are always moving against a resistance in all directions, and if we calculate the height of the atmosphere as approximately 47 miles, we can conclude that a 47 mile column of air, one inch square, at atmospheric pressure, will weigh 14.7 lbs.—which means that air has weight, and that its weight is, moreover, relative to its pressure. Another way of expressing this condition is to say that the pressure is at one atmosphere or 1 atm.

As a further starting point, although such conditions are not met in practice, we take two conditions of temperature in connection with the compression of air known as—1, *Isothermal* compression, and 2, *Adiabatic* compression. The word ISOTHERMAL means constant heat. Now if air could be maintained at its initial temperature during the whole period of its compression, by drawing from it any heat imparted by the energy used in compressing it, such compression would be the ideal standard requiring the least amount of work for any given pressure. Under these ideal conditions it would double its absolute pressure each time its volume became halved, giving us the law that *absolute pressure is inversely proportional to the volume.* In practice, however, heat is given off by the action of compression, with the result that the air acquires some additional pressure due to increased temperature, thus causing :

1. the air to acquire an outside source of pressure
2. added work to reduce it to the ideal volume for the pressure required.

ADIABATIC pressure is defined as the change in the volume and pressure in such a way that heat is neither lost nor gained by the air. So far as we are concerned, however, these standards are almost completely academic, as in the prime movers we are discussing the air temperature is raised artificially before being used.

It has been stated that a jet propulsion system uses as its chief "fuel" the surrounding air. In this respect, we must regard the air as a sort of accumulator which takes in energy from the work of compression and in the form of heat from an external source.

POWER is the rate of doing work and is calculated on the unit known as horse-power, which is the expenditure of 33,000 foot-lbs. per minute, or, of course, 550 foot lbs. per second. As the internal energy of air is directly related to its temperature, the work expended in compressing it increases this internal energy, at the same time raising its temperature.

BOYLE'S LAW.

If the temperature of a given quantity of gas is kept constant, absolute pressure is inversely proportional to volume ; conversely, the volume will vary inversely as the absolute pressure.

This under isothermal conditions (note the condition regarding keeping the temperature constant) is found by the equation :

$$\frac{P_1}{P_2} = \frac{V_2}{V_1} \text{ or } P_1V_1 = P_2V_2$$

where P_1 and P_2 are the initial and final absolute pressures (i.e. gauge pressure + 14.7 p.s.i. at sea level) and V_1 and V_2 are the initial and final volumes. Rearranging, we have :

$$\frac{\text{Final absolute pressure}}{1} = \frac{\text{Initial absolute pressure} \times \text{Initial volume}}{\text{Final volume}}$$

$$\text{that is,} \quad P_2 = \frac{P_1V_1}{V_2}$$

$$\text{and } \frac{\text{Final volume}}{1} = \frac{\text{Initial absolute pressure} \times \text{Initial volume}}{\text{Final pressure}}$$

$$\text{that is,} \quad V_2 = \frac{P_1V_1}{P_2}$$

CHARLES'S LAW (I).

If the pressure on a given quantity of gas is constant, the volume is directly proportional to the absolute temperature (F+460).

This law is calculated by the equation :

$$\frac{\text{Initial volume}}{\text{Final volume}} = \frac{\text{Initial absolute temperature}}{\text{Final absolute temperature}}$$

$$\text{that is,} \quad \frac{V_1}{V_2} = \frac{T_1}{T_2}$$

where T_1 and T_2 are the initial and final absolute temperatures.

Rearranging, we have :

$$\textit{Final volume} = \frac{\textit{Initial volume} \times \textit{Final temperature}}{\textit{Initial temperature}}$$

that is : $V_2 = \frac{V_1 T_2}{T_1}$

and $\textit{Final temperature} = \frac{\textit{Initial temperature} \times \textit{Final volume}}{\textit{Initial volume}}$

that is : $T_2 = \frac{T_1 V_2}{V_1}$

CHARLES'S LAW (2).

If the volume of a given quantity of gas is constant, the pressure is directly proportional to the absolute temperature.

This law is calculated by the equation :

$$\frac{\textit{Initial pressure}}{\textit{Final pressure}} = \frac{\textit{Initial temp.}}{\textit{Final temp.}} \textit{ or } \frac{\textit{Initial temp.}}{\textit{Initial pressure}} = \frac{\textit{Final temp.}}{\textit{Final pressure}}$$

that is : $\frac{P_1}{P_2} = \frac{T_1}{T_2}$ *or* $\frac{T_1}{P_1} = \frac{T_2}{P_2}$

Rearranging, we have :

$$P_2 = \frac{P_1 T_2}{T_1} \quad \textit{(final pressure)}$$

and $T_2 = \frac{T_1 P_2}{P_1}$ *(final temperature).*

Finally, combining both laws, so as to give a formula for a given weight of any gas, we find :

$$\textit{Final absolute pressure} = \frac{\textit{Initial pressure} \times \textit{Initial volume} \times \textit{Final temp.}}{\textit{Final volume} \times \textit{Initial temp.}}$$

that is : $P_2 = \frac{P_1 V_1 T_2}{V_2 T_1}$

and $\textit{Final volume} = \frac{\textit{Initial pressure} \times \textit{Initial volume} \times \textit{Final temp.}}{\textit{Final pressure} \times \textit{Initial temp.}}$

that is : $V_2 = \frac{P_1 V_1 T_2}{P_2 T_1}$ *(final volume)*

and $\textit{Final temp.} = \frac{\textit{Final pressure} \times \textit{Final volume} \times \textit{Initial temp.}}{\textit{Initial pressure} \times \textit{Initial volume}}$

that is : $T_2 = \frac{P_2 V_2 T_1}{P_1 V_1}$ *(final temperature).*

The above laws will assist in understanding the next step.

SPECIFIC HEAT AT CONSTANT VOLUME.

The specific heat of air at constant volume C_v is 1,689 B.T.U. per lb., which is the amount of heat required to raise the temperature through 1° F. In view of what we have already noted about increasing pressure being not only the result of pressure, but also of temperature (since by increasing temperature the air requires pressure and offers greater resistance to the compressor), it becomes evident that it will require more heat to raise it through 1° F. at constant pressure than at constant volume because, to quote our simile of the accumulator, as constant pressure, there is more "material" to expand, and hence to do useful work. The heat added must be sufficient to raise the temperature of the air as well as to supply energy equal to the external work done.

It is felt that from here on the duplication of words and symbols can be dispensed with, and so the usual system of calculating values by symbols alone will be used.

WORK DONE BY A COMPRESSOR.

Let P_1 = absolute pressure of inlet air.
v_1 = velocity inlet air,
T_1 = temperature inlet air,
P_2 = pressure outlet air,
v_2 = velocity outlet air,
T_2 = temperature,
J = Mechanical equivalent of heat,
ρ_1 = density of inlet,
ρ_2 = density of outlet air,
R = gas constant=96 using Centigrade and 53.3 with Fahrenheit.
C_v = specific heat of air at constant volume=0.169.

Energy at inlet + work done by compressor = energy at outlet.

$$\frac{P_1}{\rho_1} + \frac{v_1^2}{2} + JC_vT_1 + \textit{work done by compressor} = \frac{P_2}{\rho_2} + \frac{v_2^2}{2} + JC_vT_2$$

As outlet velocity=inlet velocity,

$$v_1 = v_2$$

$$\therefore \frac{P_1}{\rho_1} + JC_vT_1 + \textit{work done by compressor} = \frac{P_2}{\rho_2} + JC_vT_2$$

Thus, by putting both expressions in a bracket, transferring the left hand expression in to the right of the equation, and changing the sign to—

$$\textit{Work done by compressor} = \left[\frac{P_2}{\rho_2} + JC_vT_2\right] - \left[\frac{P_1}{\rho_1} + JC_vT_1\right]$$

Now let V be the volume of 1 lb. of air at inlet pressure and V_2 the volume of 1 lb. of air at outlet pressure,

$$\textit{then} \quad \frac{1}{\rho_1} = V_1 \quad \textit{and} \quad \frac{1}{\rho_2} = V_2$$

$$\textit{work done by compressor} = (P_2V_2 + JC_vT_2) - (P_1V_1 + JC_vT_1)$$

$$\textit{but from the gas laws } P_1V_1 = RT_1 \textit{ and } P_2V_2 = RT_2.$$

$$\textit{hence work done by compressor} = (RT_2 + JC_vT_2) - (RT_1 + JC_vT_1)$$

$$= T_2(R + JC_v) - T_1(R + JC_v).$$

Again from the gas laws $R + JC_v = JC_p$

Work done by compressor per lb. of air per second

$= JC_p(T_2 - T_1)$ ft. lbs.

Now, suppose a compressor dealing with W lbs. of air per sec.

Work done $= WJC_p\ (T_2 - T_1)$ ft. lbs. per sec.

$$\textit{or} \quad \frac{WJC_p}{550}\ (T_2 - T_1) \text{ h.p.}$$

AIR CONSTANT.

Boyle's law states that PV for one lb. of air at any temperature is a constant value. Charles' law states that V varies directly with T, thus:

$$\frac{PV}{T} = \textit{a constant represented by } R$$

$$PV = RT, \textit{ and hence } P = \frac{RT}{V};\ V = \frac{RT}{P},\ T = \frac{PV}{R}$$

P being expressed in lbs./sq. ft. and V in cubic feet.

As the volume of 1 lb. of air at 32 F. and 14.7 p.s.i. is 12.39 cu. ft., then

$$R = \frac{14.7 \times 144 \times 12.39}{492} = 53.3$$

and so the above values can be given numerical values by substituting the value of R

$$\frac{PV}{T} = 53.3, \quad P = \frac{53.3T}{V}, \quad V = \frac{53.3T}{P} \text{ and } T = \frac{PV}{53.3}$$

But this is applicable only to 1 lb. of air, so it is useful to make a general equation for any weight of air as follows :

$$PV = W53.3T, \quad P = \frac{W53.3T}{V}, \quad V = \frac{W53.3T}{P}, \quad T = \frac{PV}{53.3W}$$

$$53.3 = \frac{PV}{WT} \text{ and } W = \frac{PV}{53.3T}$$

DENSITY.

The density of a gas varies with its temperature or anything else affecting its volume. Density is represented by the Greek letter ρ (Rho) and is expressed by the equation $\rho = \frac{P}{RT}$ lbs. per cu. ft., e.g. if the density of air is 0.18 lbs./cu. ft. at a given pressure at 60° F. at the same pressure but at 1,200° F. it will be $\rho_2 = \frac{\rho_1 T_1}{T_2}$

$$= \frac{0.18(60 + 460)}{1,200 + 460} = \frac{0.18 \times 520}{1,660} = 0.0564 \text{ lbs./sq. in.}$$

Note the value 460 is added because T is *absolute* temperature.

One further useful ratio is the Compression constant, which may be stated as

$$\frac{\text{Specific heat at constant pressure}}{\text{Specific heat at constant volume}} = \frac{C_p}{C_v} = a \text{ constant.}$$

For dry air this constant = 1.406, but as inlet air is seldom completely dry, an average is taken of air at 36% relative humidity at 68° F. when the constant = 1.3947.

Having now established the relationships existing between pressure, volume, temperature, energy and density, we can use these ratios in various combinations to calculate the characteristics of compressors.

CHAPTER III.

THE CENTRIFUGAL COMPRESSOR.

Two types of rotary compressor are associated with gas turbines to form a complete prime mover. They are :

1. The centrifugal compressor.
2. The axial flow compressor.

The main difference in the characteristics of these systems is that the centrifugal compressor is simple in construction, offers a minimum frictional loss through having only one shaft and two bearings, and has a high capacity/weight and capacity/size efficiency. On the other hand, it is not suitable for dealing with the delivery of air at very high pressures; for although it can deal with a very considerable volume and mass of air, certain losses are inevitable. The axial flow compressor, on the other hand, though more complex and likely to call for more attention, can cope with high pressures without loss, but has the disadvantage of a less favourable capacity/size and /weight efficiency. The merits of axial flow compression will be examined in a later chapter.

A single stage centrifugal compressor consists of :

1. An impeller rotating axially on a shaft.
2. A plurality of rotating blades attached at right angles to a circular disc and radially about the shaft.
3. A plurality of fixed blades outside the circumference of the disc and rotating blades.
4. A spiral casing ending in a delivery outlet.

The simple components and assembly are shown in Fig. 3.

Air enters axially through the inlet A, sucked in by the rotating blades R, but cannot follow its axial course owing to the obstruction of the disc which, if shown, would obscure the blades and inlet. The blades entrain it and as a result of centrifugal force, it is hurled outwards, being subjected to increase in velocity and pressure, but this velocity, both radial and tangential, has replaced the axial velocity at the inlet. The fixed blades, C, then guide it into the casing towards the outlet.

During its passage through the impeller, the air has acquired two properties, velocity and pressure, which represent the energy imparted by the moving blades but, as the name compressor implies, the more needful of these is energy in the form of pressure. Owing to its centrifugal nature it is obvious that the greatest pressure will occur at the outside tip of the moving blades, and consequently the "tip speed" will govern the pressure rise.

For purposes of calculation it is assumed the change of direction from axial to radial takes place at the shaft and is a right angle, and further that the direction of the air between two blades is that of the mean line equidistant at all points between the two.

Now suppose the air entering radially to have a velocity V_1, represented by the line B.A., parallel to the shaft. Due to rotation the edges of the blades (see Fig. 4) have a tangential velocity U, relative to the air. This is represented by B.C. at right angles to B.A.; then the velocity of the air relative to these edges will be the line B.C., completing the triangle. On whatever scale the diagram is drawn, we have A.C.= vol. of air relative to impeller or U.

Similarly, the outlet velocity can be determined. Let D.E., drawn to any convenient scale, represent the velocity of air leaving the impeller $= U_2$. F.D. will then represent the tangential velocity U_2 and F.E.; then completion of the triangle will show the direction and value of the air at outlet. The ideal standard of adiabatic compression cannot be obtained through the compressor, so that in practice the temperature at outlet is higher than at the inlet. For purposes of combustion

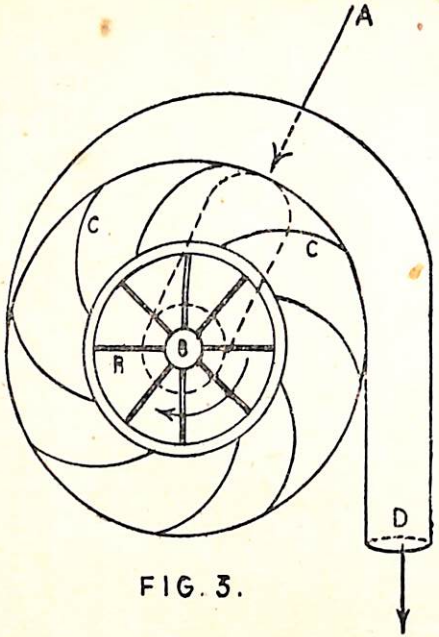


FIG. 3.

A AIR ENTERS AXIALLY B SHAFT OF ROTOR
C STATIONARY GUIDE VANES D OUTLET CONDUIT
R MOVING BLADES

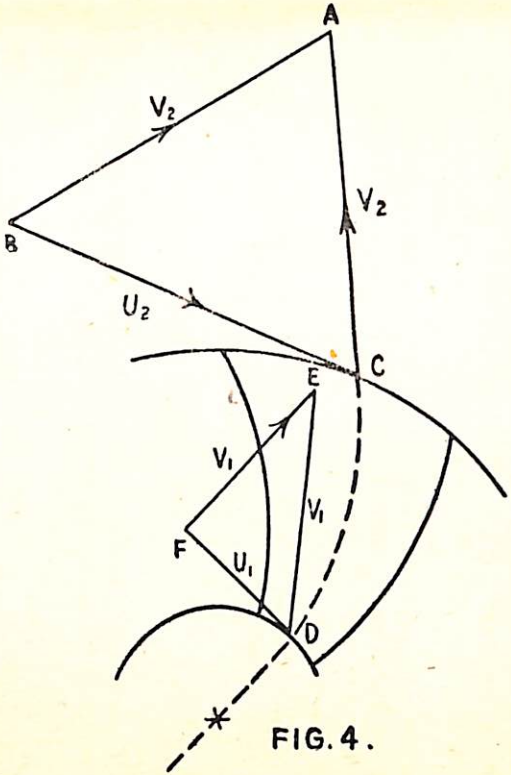


FIG. 4.

turbine technique, this is to some extent an advantage, but for the purpose of calculating the horsepower of work required for compression, it brings some complications. Nevertheless, by making use of the expression known as the compression index, which may be taken as 1.4 for air, the compression may be regarded as adiabatic.

LOSSES.

The chief losses encountered in the compressor can be summarised as follows :

Shock losses 6%,
Disc friction on air 7.5%,
Surface friction 5%,
Bearing friction 1.5%,
Leakage 2%,

making total losses of 22%, and hence leaving useful adiabatic work of 78%. The frictional losses are, however, not true losses but caused by the air in the compressor becoming heated, with consequent increase in pressure which will be lost on cooling, but which makes it necessary to use more h.p. to compress a given mass of air.

In the case of a single stage compressor nothing can be done about this, but in a multi-stage machine, the air between the stages can be cooled by a device known as an intercooler. The outlet air from the first stage passes through a system of conduits rather similar to the radiator of a motor car, and, being cooled after each stage, its pressure and volume are reduced, with consequent saving of fuel at the power input end. The great disadvantage of intercoolers is their weight and bulk.

SURGE.

So far the question of delivery has not been considered. Suppose that in a compressor the delivery can be varied, then obviously two extreme points will occur—1, where there is no delivery of air and, 2, where the quantity of air is so great that expansion will take place and pressure will fall. This

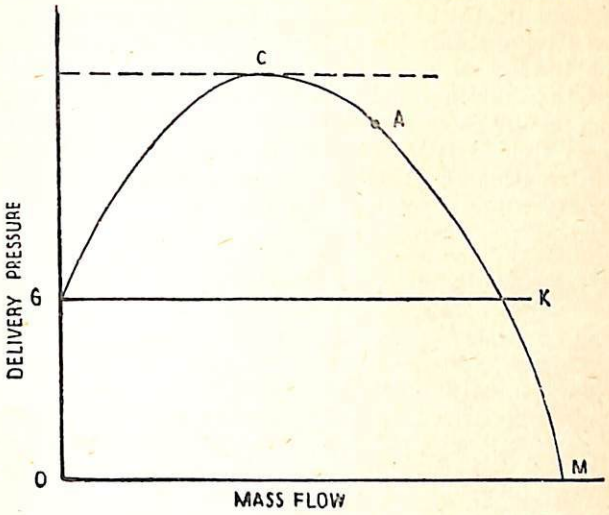


FIG. 5

CHARACTERISTIC CURVES SHOWING PRESSURE AND MASS FLOW RATIOS OF THE DESIGNED EFFICIENCIES

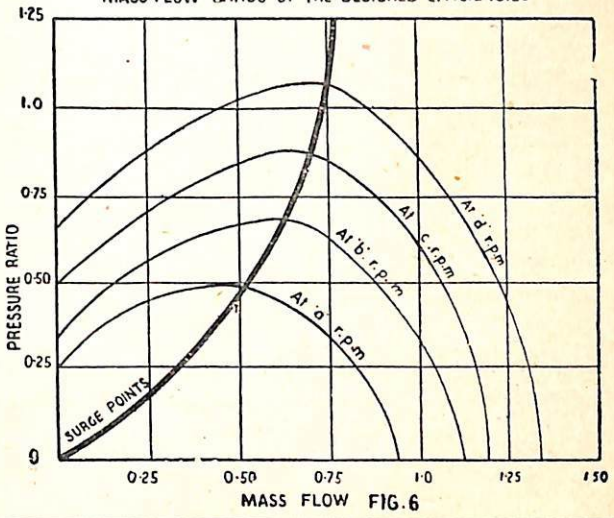


FIG. 6

is rather similar to the passage of an electric current through a circuit having a variable resistance interposed, and similarly a graph known as the characteristic curve can be drawn. There is an additional factor in the case of air, however, viz., that its pressure can be varied by the speed of rotation of the impeller. But apart from mechanical stresses and strains set up at different speeds, there is an optimum speed for safe and efficient operation dependent upon the characteristics of the machine.

The characteristics curve may be shown in Fig. 5.

This curve represents the function of the compressor at a constant speed. The pressure at G is zero, rising to optimum at C, and gradually falling to M, where it is zero again. If, as at points between C and M, the output in mass increases, the pressure falls and, similarly, from C to G, if the mass is reduced, the pressure falls with it. Although maximum pressure/mass is obtained at point C, most compressors are regulated to operate at point A. If delivery were stopped down, this point would move up to C and vice versa, but if the point A were to go to the left of C, the condition would result that momentarily the pressure in the system would fall below the delivery pressure, and in regaining the equilibrium a reverse pressure would be created. Since the demand would still exist at the delivery end, the result of this attempt to find equilibrium would send the point from the negative point G to its opposite positive point K, and this transposition would continue to be repeated very rapidly, causing a kind of hiccough, or unstable flow, known as " surge." The surge point is C., and this explains why, although apparently it is the point of maximum theoretical efficiency, it is not so in practice.

Characteristic curves are shown in Fig. 6, with a " surge point " curve cutting them.

Finally, if both the speed and delivery are varied in the same proportions, a balance will be struck, the efficiency remaining constant ; hence the rule : *Pressure ratio varies as the square of the speed.*

THE AXIAL FLOW COMPRESSOR.

The axial flow system is essentially a multi-stage system. Air is drawn into the compressor axially, as in the case of the centrifugal machine, by a set of moving blades, attached to a rotor, which impart to the air a tangential velocity in the direction of rotation, which is added to the axial velocity to give the absolute velocity on exit from the blades. The direction of the velocity is changed from its original axial direction to one at an angle to it. Being the sum of two values, this absolute velocity is greater than the entrance velocity. This is demonstrated diagramatically in Figs. 7 and 7a.

The air then passes to a row of stationary blades attached to the casing and is guided back to its original position, but at the cost of losing its acquired tangential velocity ; thus it enters the moving blades at the second stage at the same axial velocity with which it entered the first set of moving blades, where the cycle is repeated to each of the successive stages, and finally it emerges at the outlet. As velocity is energy, although the kinetic energy is increased and later, so to speak, cancelled out by the fixed blades, this energy is not lost, as it would be if utilized as kinetic energy, to make the air expand, but it is transformed into pressure which, of course, is simply another form of energy. So the pressure increases from stage to stage.

Just as with the centrifugal compressor, the work done in the compressor can be expressed in terms of temperature charge.

Let v_1 = absolute inlet velocity,
v_2 = absolute outlet velocity,
T_1 = absolute inlet temperature,
T_2 = absolute outlet temperature,
ρ_1 = air density inlet,
ρ_2 = air density outlet,
R = gas constant,
J = mechanical equivalent of heat,
C_v = specific heat of air at constant volume,
C_p = specific heat of air at constant pressure.

The total energy of 1 lb. of air at outlet is equal to

$$\frac{P_1}{\rho_1} + \frac{v_1^2}{2} + JC_vT_1 + \textit{work done} = \frac{P_2}{\rho_2} + \frac{v_2^2}{2} + JC_vT_2$$

for any one stage.

But, as velocity at outlet is equal to velocity at inlet, owing to the "braking" action of the fixed blades, this equation can be expressed :

$$\frac{P_1}{\rho_1} + JC_vT_1 + \textit{work done} = \frac{P_2}{\rho_2} + JC_vT_2$$

work done per lb. of air per sec. is :

$$\left[\frac{P_2}{\rho_2} + JC_vT_2\right] - \left[\frac{P_1}{\rho_1} + JC_vT_1\right]$$

With V_1 as specific volume of air at inlet and V_2 specific volume of air at outlet

$$\frac{1}{\rho_1} = V_1 \textit{ and } \frac{1}{\rho_2} = V_2$$

and by substitution

$$\textit{work done} = (P_2V_2 + JC_vT_2) - (P_1V_1 + JC_vT_1)$$

But from gas laws $P_1V_1 = RT_1$ and $P_2V_2 = RT_2$

$\therefore$ *work done is*

$$(RT_2 + JC_vT_2) - (RT_1 + JC_vT_1) = T_2(R + JC_v) - T_1(R + JC_v)$$

Again from the gas laws

$$R + JC_v = JC_p = \textit{work done}$$

and by substitution work done per lb. per sec. is :

$$JC_p(T_2 - T_1) \textit{ ft. lbs./sec.}$$

Multiplying by the mass flow per sec $= W$, we have :

$$WJC_p(T_2 - T_1) \textit{ ft. lbs./sec.}$$

or

$$\frac{WJC_p(T_2 - T_1)}{550} \textit{ h.p.}$$

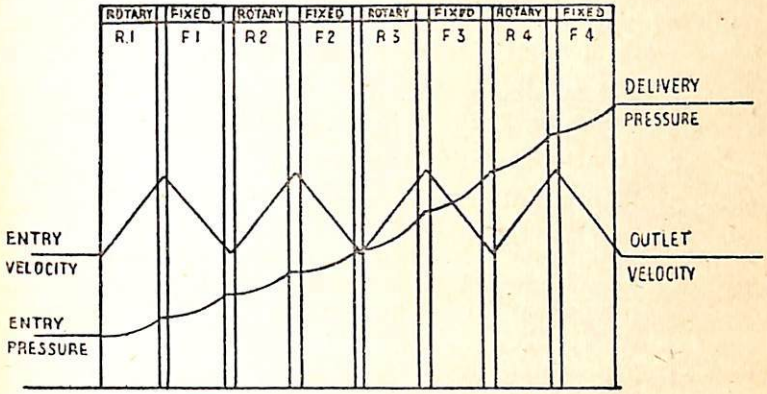

ROTARY
FIXED
ROTARY
FIXED
ROTARY
FIXED
ROTARY
FIXED
R 1
F 1
R 2
F 2
R 3
F 3
R 4
F 4
DELIVERY
PRESSURE
ENTRY
VELOCITY
OUTLET
VELOCITY
ENTRY
PRESSURE

FIG. 7.

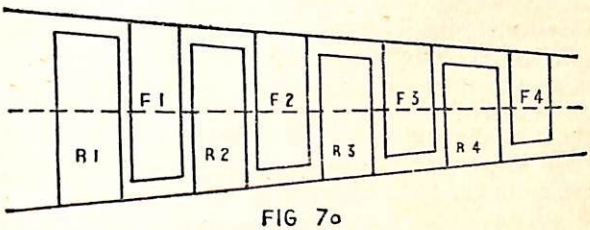

F 1
F 2
F 3
F 4
R 1
R 2
R 3
R 4

FIG 7a

CHARACTERISTICS.

In the case of the centrifugal compressor, a characteristic curve was compiled (see Fig. 6). The same applies to axial flow, as also does the element of " surge."

Space does not admit of repetition of these calculations to suit axial flow compressors, and so we must content ourselves with giving the following comparative results:

1. The maximum efficiency of the axial flow system is higher than that of the centrifugal compressor.
2. Its characteristic curve is not so flat.
3. Where outlet pressure is so high that the average input/output ratio of 1 : 2 of a *single* stage centrifugal compressor is insufficient, the axial flow system offers a more compact medium since a multi-stage centrifugal compressor is more bulky than its axial flow counterpart.
4. The stage pressure ratio of the centrifugal is 1 : 2, but that of axial flow only about 1 : 1.2.

Should a combination of both be considered more suitable, the considerations governing design would be to choose a multi-stage axial system followed by a single stage centrifugal, for naturally, it would be more efficient to deliver air compressed by several stages at the smaller ratio for final compression to double it, than risk losses by having a double input pressure gradually increased by several stages at the smaller ratio.

Having obtained air at the outlet of the compressor, we have, in fact, a " fuel " to which has been transmitted stored energy in the form of pressure by mechanical means. This energy can now either be turned into kinetic energy by permitting it to expand and do useful work, or it can be again subjected to storage of energy, but this time by introducing the energy to the form of heat.

It is interesting to digress here for a moment to point out that if no mechanical losses occurred through the system, the release of kinetic energy from the compressed air would be

equal to the work done in compressing it, so that if directed through a turbine attached to the same shaft as the compressor, it would operate the compressor and so complete a perpetual motion cycle. Such, however, are the losses due to friction, imperfect adiabatic conditions, leakage between the impeller blades and the fixed blades and other causes, that such efficiency is impossible of realization.

But to continue with the gas turbine cycle. The further storage of energy is now effected by subjecting the compressed air to the heat of combustion of a high-pressure jet of liquid fuel, ignited in the first stage by a sparking plug and later by the heat of the chamber in which the combustion takes place. This combustion may take place either as a series of " explosions " or as a continuous combustion, but whichever method is used, its object is to give heat energy to the fluid. Moreover, the ideal conditions to be aimed at are continuity of flow, speed and thoroughness of combustion and velocity of the fluid directed through the nozzle against the turbine rotor blades. One means for insuring the fulfilment of these ideal conditions is the simultaneous combustion of several fuel jets in different combustion chambers, and this means does, in fact, find practical application in the modern aeroplane power unit. These combustion chambers are located radially around the unit and vary in number, the earlier Derwents having 10, the Derwent V. 9, the Nene 9 and the Bristol Theseus 8, etc.

Thus, the very great mass of air can be dealt with in the most efficient and economical manner without creating disturbing factors, such as undue turbulence, imperfect combustion and the like. But the design of combustion chambers is also one in which careful calculations based on the properties of gases can be made, and as it is a subject of prime importance it will receive suitable attention in the next chapter.

CHAPTER IV.

THE PASSAGE OF THE FLUID THROUGH THE COMBUSTION CHAMBER.

The designer of combustion chambers has two essentials to bear in mind, viz., that he is designing for constant pressure and continuous combustion, and that the ultimate object of the whole compression and combustion system is to convert as much as possible of the stored energy in the air stream into *velocity* energy.

When air is heated, as explained, changes take place in its volume, density and velocity.

VOLUME.

According to Charles's law, if the temperature of a gas is raised whilst the pressure is held constant, the volume is directly proportional to the absolute temperature expressed as

$$V_2 = \frac{V_1 T_2}{T_1} = \textit{Final volume} = \frac{\textit{Initial volume} \times \textit{Final temp.}}{\textit{Initial temperature}}$$

from which it is evident that to obtain a high final volume, it is necessary to have the final temperature as high as possible and the initial temperature as low as possible, whilst the initial volume should be as high as possible.

DENSITY.

It is assumed that the air is incompressible (as we are assuming constant pressure) and therefore the density will itself remain constant.

VELOCITY.

Here recourse is had to Bernoulli's theorem, which states that if in two chambers of different diameter, A + B, a stream of gas passes at constant pressure, then :

$$\frac{\textit{Static pressure}}{\textit{density}} + \frac{(\textit{Velocity in } A_2)^2}{2} =$$

$$\frac{\textit{Static pressure}}{\textit{density}} + \frac{(\textit{Velocity in } B_2)^2}{2}$$

or substituting the symbols P_1 = static pressure in A, P_2 = static pressure in B, ρ = density = constant, v_1 = velocity in A, v_2 = velocity in B.

$$\frac{P_1}{\rho} + \frac{v_1^2}{2} = \frac{P_2}{\rho} + \frac{v_2^2}{2}$$

So now it is possible to calculate the mass air flow in a combustion chamber having a narrow neck leading into a wider chamber, as in Fig. 8. But here a most important factor calls for consideration, namely, that the mass of air has to expand in chamber B and that, owing to its natural tendency to take the shape of the containing vessel, coupled with its velocity, a considerable amount of turbulence will be created in the corners of chamber B. This turbulence is the cause of a high proportion of efficiency being lost.

What then is the remedy? Suppose these corners are eliminated, as in Fig. 8a. The inlet air will be at pressure P_1, moving at velocity v_1 and with density ρ_1, whilst in the chamber proper these values will be v_2, P_2 and ρ_2 respectively. Assuming lateral expansion in B, then there will be a loss of velocity and pressure in B, so to counteract these losses the velocity and pressure must be increased. This can be done by introducing a burner to increase the temperature, thus compensating for the losses caused by lateral expansion and consequent longitudinal contraction, with their resultant reducing effect on velocity. *The velocity is therefore held constant throughout.*

The addition of heat results in an increase of the volume of the air, and the final object being to transform this acquired energy into velocity to turn the turbine, a means has to be found for this. This is achieved by passing the air through a nozzle, and the means of calculating the conversion will be found in a later chapter, our next problem being the determination of the dimension of the combustion chamber.

Let A_1 = the cross sectional area of duct A,
A_2 = the cross sectional area of duct B,
P = pressure,
ρ_1 = density of air in duct A,
ρ_2 = density of air in chamber B,
v = constant flow velocity,
H = heat added in B.Th.U.,
J = mechanical equivalent of heat.

We can therefore modify Bernouilli's theorem to express the equation between the energy of the stream per lb. of air entering the duct A to the energy of the air leaving chamber B as follows:

$$\frac{P_1}{\rho_1} + \frac{v^2}{2} + JH = \frac{P}{\rho_2} + \frac{v^2}{2}$$

Note that we have dispensed with P_1 and v_1, as the pressure and velocity are compensated by the heating so as to be uniform throughout the system.

The value H is calculated by predetermining the amount of energy required to drive the turbine (assuming that the system is limited to the simple turbine cycle and that no further power is required beyond this), and the values of P and v are known from the compressor characteristics, as also is the density of the outlet air from the compressor, but P_2 is a variable depending on the temperature of combustion.

We may, therefore, re-express the equation:

$$\frac{P}{\rho_1} + JH = \frac{P}{\rho_2}$$

$$\frac{1}{\rho_2} - \frac{1}{\rho_1} = \frac{JH}{P}$$

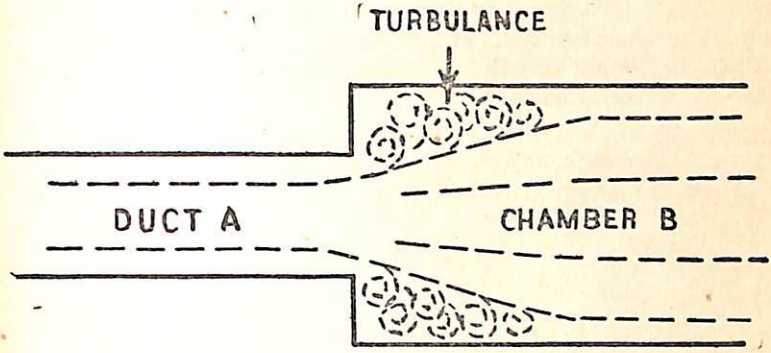


FIG 8

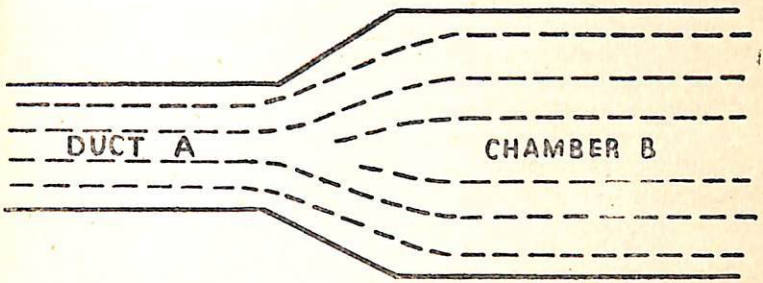


FIG. 8 a

Now, we need two temperatures : the absolute temperature of the air leaving the compressor and the temperature of the air leaving the nozzles which is required to operate the turbine. The former T_1 is known, whilst T_2 can be calculated from the pressure drop as the fluid expands on exit from the nozzles. If V_1 is the volume of 1 lb. of air before heating and V_2 is the volume after heating, then

$$V_2 = \frac{V_1 T_2}{T_1}$$

If W lbs. of air per sec. are passed through the duct, then

$$WV_2 = A_2 V = \frac{WV_1 T_2}{T_1}$$

But $WV_1 = A_1 V$

$$\therefore \quad A_2 V = A_1 V \quad \frac{T_2}{T_1}$$

and $$A_2 = A_1 \quad \frac{T_2}{T_1}$$

or cross sectional area of chamber = area of duct $\times$ $\frac{\textit{outlet temp. abs.}}{\textit{inlet temp. abs.}}$

MATERIALS FOR COMBUSTION CHAMBERS.

Many factors have to be considered when selecting materials to withstand the conditions created by temperature, pressure, oxidation and expansion. For example, the material must have a tensile strength sufficient to withstand the stresses imposed on it when at its *lowest* resistance, i.e., at high temperature. It must resist burning by the hot gases and oxidation from the free oxygen in the high excess of air burnt with the fuel ; it must be chosen so as to suffer a minimum of distortion due to expansion when hot and contraction when cold : it must be tough, light, workable, reasonably cheap, and so forth.

In the case of the Impulse turbine, the sudden drop in pressure, due to expansion at the outlet of the nozzle, is accompanied by a corresponding rapid fall in temperature, so that Impulse combustion chambers are of a higher heat resisting material than the blades. But in the Reaction

turbine, in which the hot fluid enters the first stage of the turbine at the same temperature as that in the combustion chamber, both materials may be the same. It is a comparatively simple matter to find materials to fulfil one or more of the conditions, or even to find combinations of materials with the desired properties, but to find either materials or combinations having all the properties has so far proved impossible.

At first glance, it might be thought that a solution could be found by lining the metal combustion chamber with an oxidation resisting refractory material, but it is an extremely difficult matter to find a refractory lining that will expand at the same rate as the metal chamber, and so the result of such a combination would be that the metal (with a high co-efficient of expansion) would part from the refractory lining (most of which have a low co-efficient of expansion), leaving a gap, so that the lining would suffer all the stresses and strains which should be borne by the metal, and would undoubtedly crack or burst. This problem is known as the problem of differential expansion.

A second combination would be to insert an intermediate lining of some elastic material between the refractory and the metal, an attempt being made to choose all three of as near similar co-efficients as possible. This, however, brings with it additional weight and bulk which, at least in turbine units for aircraft, is very undesirable. A further combination would be to cool the lining and the casing by means of water circulation, but here again there is the objection of weight, bulk and complexity.

Although these problems do present themselves in the case of the reaction turbine, they are somewhat modified by the fact of combustion chamber temperature and first turbine stage temperature being equal, so that it is possible to reduce combustion chamber temperature to suit available materials, but even so, as has been shown, the higher the temperature the higher the power (apart from losses discussed in the next chapters), and so this is not a true solution, and for the present a compromise has to be made. For aircraft, life of the chambers is sacrificed to lightness and tensile strength by using unlined heat-resisting steel, but research is progressing

along two lines—1, to increase the pressure ratio between the combustion chamber and the buckets of the Impulse turbine (for stationary plant), so that the increased efficiency would justify the use of refractory-lined chambers, and 2, metallurgical research to produce heat and oxidation-resisting alloys for Reaction turbines.

Before leaving the subject of combustion chambers it should be mentioned that the problems of differential expansion are not confined to shells and linings, for in a system using a steel combustion chamber, different temperatures occur in different parts of the chamber.

At the inlet, there is a constant stream of cold air from the compressor, exercising a cooling effect on the inlet, in the combustion area; unless very good mixing is achieved there is the increased temperature over the range from inlet to outlet temperature, and at the outlet there is the maximum temperature. It is evident then that from this one angle alone there is a wide field for research, for difference of expansion between joints of different materials can cause losses of considerable importance in such a system.

THE FUEL INJECTION NOZZLE.

The advent of the compression ignition engine system, of which diesel engines are a part, has caused the problems of injection nozzle design to be very thoroughly examined, so that highly efficient nozzles have been produced.

The injector for a turbine combustion chamber is fundamentally the same as that for a diesel engine, and will be dealt with only superficially here.

To inject ionized liquid fuel into a mass of fluid under compression necessitates some form of pump to increase the velocity of the liquid fuel, so that when ionized it will overcome the pressure of the fluid into which it is injected and become thoroughly mixed with it. This is achieved by the fuel pump. But the conditions in the combustion chamber vary with speed and altitude, and although speed may, for general purposes, be regarded as constant, altitude, and therefore air inlet and outlet conditions, are not. The injector must therefore be subject to automatic control to ensure that an adequate

amount of fuel is injected to suit the varying conditions. This is achieved partially by varying the stroke of the pump by an aneroid control similar to that used in an altimeter, and partially by fitting the nozzle with a needle valve which is controlled by a spring compressed or relaxed by the pressure of fluid in the combustion chamber.

Positioning of the injector jet is a matter dependent upon the design of the chamber, and upon considerations of compactness and the like ; for instance, in the Derwent V. unit, it is positioned so as to spray its initial starting fuel directly on to the sparking plug.

To ameliorate the anomalies of differential expansion in the combustion chamber, two or more injectors may be fitted if necessary, although, in general, simplicity of design for aircraft prime movers being a high priority requirement, single injectors in each of several small combustions are regarded as preferable.

CHAPTER V.

THE GAS TURBINE CYCLE.

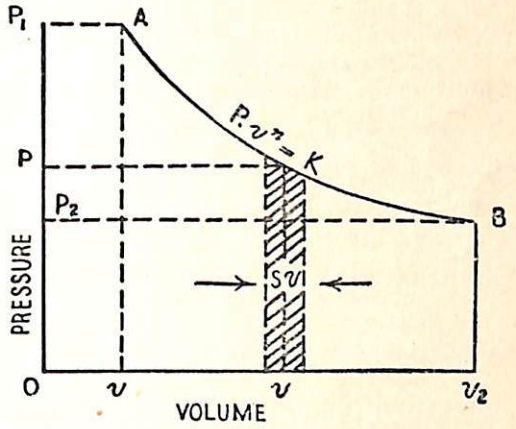
Having discussed the compressors we can now turn to the gas turbine cycle, and as the functions and operation of the Impulse turbine and Reaction turbine in many respects are alike, we shall not differentiate between them here, but will give a general survey of both.

So far we have considered only the actual driving of the air compressor as the object of the unit, but now we have to regard this as a subsidiary purpose, since the main purpose is the production of a high-velocity jet of the working fluid with which to drive the 'plane. Our concern is with what is called the " turbine." Turning to Fig. 9 the cycle can be traced.

Point 1 represents the entry of air into the compressor at atmospheric pressure, and is compressed therein to point 2. From the compressor outlet it enters the combustion chamber where, without change of pressure, but with increase of volume, it is heated to the volume shown at point 3. It then enters the turbine and releases its stored energy along 3, 4, finally (under ideal conditions) expanding in the turbine along line 4, 1, until it has resumed its original volume and pressure in the ambient air. The total work of this cycle is represented by the area 4, 5, 6, 3, and the work done in compressing the air by the area 1, 5, 6, 2. The difference of these is now the work available for utilizing outside the system. Now it can be proved that the efficiency of the cycle is the result of the pressure ratio and nothing else, as shown below. Taking as the efficiency of the air cycle

$$\eta = \frac{\textit{Heat energy added} - \textit{heat energy rejected}}{\textit{Heat energy added}}$$

The heat energy added is the temperature at the entry of the air into the turbine, less the temperature of the air entering



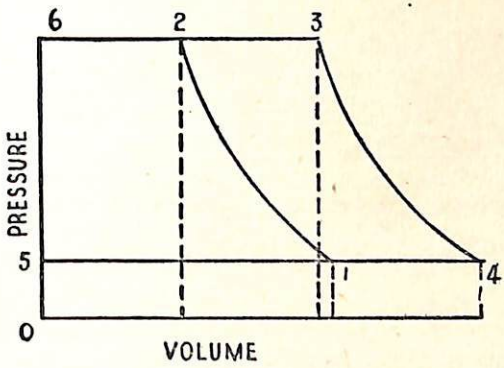


FIG. 9

the compressor, which we will express as $T_3 - T_2$, and multiplied by the specific heat of air at constant pressure C_P. So we have

$$\textit{Heat added} = C_p\,(T_3 - T_2).$$

The heat energy rejected (after all the work is done) takes place along line 4, 1, and is the difference between temperature at exit from turbine and temperature at entrance to compressor, which we will express as $T_4 - T_1$ multiplied by specific heat at constant pressure C_P. So we have

$$\textit{Heat rejected} = C_p\,(T_4 - T_1).$$

So our original equation can be expressed :

$$\frac{C_p\,(T_3 - T_2) - C_p\,(T_4 - T_1)}{C_p\,(T_3 - T_2)} = 1 - \frac{T_4 - T_1}{T_3 - T_2}$$

From the chapter dealing with gases, we find that

$$T_2 = T_1\left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}} \quad \textit{and} \quad T_4 = T_3\left(\frac{P_1}{P_2}\right)^{\frac{\gamma-1}{\gamma}}$$

the heat energy added, $C_p\,(T_3 - T_2) = C_p\left[T_3 - T_1\left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}}\right]$

and heat rejected $C_p\,(T_4 - T_1) = C_p\left[T_3\left(\frac{P_1}{P_2}\right)^{\frac{\gamma-1}{\gamma}} - T_1\right]$

$$= \frac{C_p\left[T_3 - T_1\left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}}\right] - C_p\left[T_3\left(\frac{P_1}{P_2}\right)^{\frac{\gamma-1}{\gamma}} - T_1\right]}{C_p\left[T_3 - T_1\left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}}\right]}$$

By dividing by the denominator we get

$$\eta = 1 - \left(\frac{P_1}{P_2}\right)^{\frac{\gamma-1}{\gamma}}$$

At first sight it might appear that the addition of more heat between compressor outlet (line 2, 3) would increase the efficiency, but it must be remembered that this involves a greater rejection of heat at turbine outlet (line 4, 1), and in the case of aircraft, at any rate, this heat is wasted, as it

cannot be used to pre-heat the air at its crucial point, i.e., on entry into the combustion chamber. If it were used to pre-heat the air before entry into the compressor, it would decrease the density and so lower the pressure. From this it is evident that ideal conditions call for :

Very low temperature at entrance to compressor.

Very high temperature at outlet from turbine,

despite the waste of heat, as only by high temperature can the required high pressure be attained.

The difference between the work done in compressing the air and the work shown by the area 4, 5, 6, 3 has now to be converted into " Thrust," and this leads to Newton's third law of motion and the design of nozzles capable of transforming this work into propulsive energy. The passage of the hot gases through a reaction turbine is very similar to the passage of air through a compressor, only in reverse. Instead of regarding Fig. 7a as operating from left to right, we have to regard the passage of the combustion gases as moving from right to left, and in Fig. 7 delivery pressure for the compressor is replaced by combustion chamber pressure, whilst the entry pressure of air in the compressor is replaced by exhaust pressure from the turbine.

If an inflated balloon is fitted with a valve, the opening of that valve will cause air to be subjected to three changes :

1. The pressure will be reduced.
2. The velocity of the air will be increased from zero to a maximum, and then reduced once again to zero.
3. The released gas will expand to atmospheric pressure.

The first and last are, in point of fact, the same, but are separated here as representing the difference between pressure and exhaust pressure by analogy.

So in the turbine. Combustion gases already having a certain pressure and velocity enter the turbine fixed blades and undergo a loss of pressure and an increase in velocity. Since the angle of the outlet of the blades is less than that at inlet, they impart an effect similar to that of a nozzle so as to increase the velocity for rotating the row of moving blades

next to them, and so turn some of its latent energy acquired by compression and heating into kinetic energy, resulting in loss of pressure and velocity. The next row of stationary blades recuperate the velocity and the fluid at reduced pressure, but compensated velocity enters the second stage stationary blades, and then the second flow of moving blades, which are of less diameter to allow for the decrease in pressure. And so the fluid passes through the turbine, giving up its kinetic energy, which is transformed (a) into energy to operate the compressor and (b) useful work for other utilization.

The Impulse turbine, on the other hand, utilizes the high-speed jet of the fluid from the combustion chamber to impinge upon the blades or buckets of the turbine wheel. In its passage over the curved surface of the blades, the direction of the fluid is changed so that it emerges almost axially. The drop in velocity between the nozzle and the wheel exit, due to expansion, generates a force acting upon the blades which causes them to rotate. After having given up its kinetic energy, or a part of it, to the blades, the fluid still retains a proportion of its energy, and this is often utilized by passing it through a row of fixed guide vanes so as to direct it to a second row of rotating blades attached to the same rotating wheel. Such an arrangement is known as a two-row wheel.

The pressure velocity drop for both single and multi-row wheels is illustrated in Figs. 10 and 11 respectively.

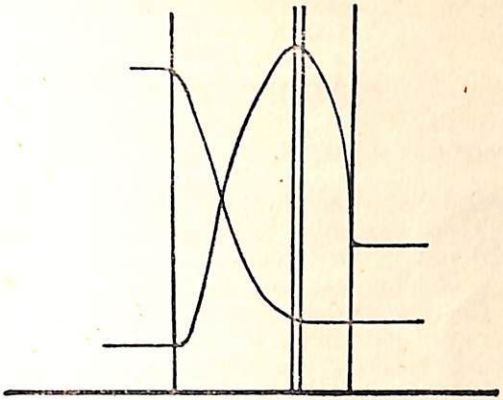


FIG. 10.

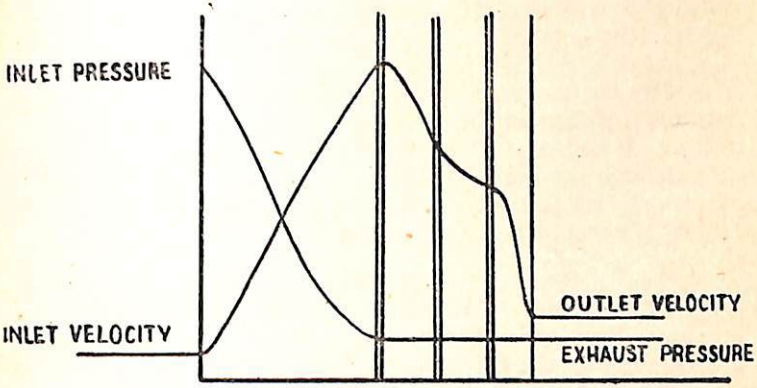

INLET PRESSURE
INLET VELOCITY
OUTLET VELOCITY
EXHAUST PRESSURE

FIG. 11.

CHAPTER VI.

THE JET PROPULSION SYSTEM.

Sound is a disturbance in the medium through which it is transmitted, and in relation to jet propulsion, this medium is air. Sound travels through air at a speed of 760 miles per hour at sea level, but this speed is reduced at higher altitudes owing to the reduced density of the medium. Many other disturbances can occur in the air, each of a different velocity, but the speed of sound is the standard according to which the performance of propellers and jets is calculated, because beyond the speed of sound in this medium various physical changes take place in air.

Air at sea level then conducts a disturbance called sound at 760 m.p.h.; a disturbance of higher velocity will therefore try to make the air denser so as to increase its conductivity, and in doing so it piles up the molecules of air which, instead of conducting, are, so to speak, opposing it. This effect can be likened to the bow wave of a fast moving ship at sea. The resultant attempt of the disturbance to increase the density of the air is known as a " shock wave," and although considerable research has been devoted to the phenomenon by photographing bullets in flight, explosions and the like, comparatively little is known of its results.

When the tip speed of a propeller exceeded the speed of sound, this shock wave is created and the performance of the propeller decreases. Since the tip speed of the propeller greatly exceeds the forward speed of the aircraft, a means was sought for replacing the propeller, with its very definite limitation, by some other form of propulsion whereby the forward speed of the aircraft could be increased without its propulsion system attaining super-sonic velocity. The means discovered is the jet.

In jet propulsion the air is drawn into the aircraft in a direction opposite to its direction of flight ; this fact causes an initial useful compression known as " Ram." It then passes through the processes described in the foregoing chapters to emerge as a high velocity rearward jet.

According to Newton's third law of motion, action and reaction are equal and opposite, and so, when the energy of this air is released at the jet it exercises equal pressure in both forward and rearward directions (forward being now regarded as the direction of flight), and the forward energy is known as " thrust." What happens to the air after it leaves the jet is of little importance, since we are primarily concerned with the reaction causing thrust.

The energy present in forward thrust performs two functions :

a. to give the aircraft forward velocity,

b. to impart lift to maintain it in the air,

and as these two functions convert the velocity of the jet into useful work, the velocity of the jet can attain values far in excess of that of sound before the aircraft itself attains the speed of sound.

To determine the energy of this system, let u be the forward speed of the aircraft in ft. per sec., u will also be the velocity of air entering the system (in opposite direction) ; let v be the velocity of air leaving the rearward jet relative to the aircraft in ft. per sec.; let g be the gravitational acceleration (32 ft. per sec. per sec.) ; let K_1 = the kinetic energy of 1 lb. of air at exit from the jet, K_2 = the kinetic energy of 1 lb. of air at entry into system.

$$\text{then } K_1 = \frac{v^2}{2g} \text{ ft. lbs.}$$

$$\text{and } K_2 = \frac{u^2}{2g} \text{ ft. lbs.}$$

The energy at outlet less the energy at inlet will represent the energy needed in the system

$$\frac{v^2}{2g} - \frac{u^2}{2g} \text{ ft. lbs.} = \frac{v^2 - u^2}{2g}$$

Since the increase in velocity is the difference between exit and inlet velocity, $v-u$ ft. per sec., the change in momentum per lb. of air is

$$\frac{v-u}{g} \text{ lbs. or for } W \text{ lbs. of air} = \frac{W(v-u)}{g} \text{ lbs.}$$

representing the REARWARD FORCE of the jet. But since, according to Newton's law, action and reaction are equal and opposite, then

$$\frac{W(v-u)}{g} \text{ lbs.}$$

also represents the FORWARD FORCE exercised on the aircraft. This is known as THRUST, and as the forward speed of the aircraft is u, then the product of thrust and forward speed of the aircraft will be the work done in propelling it.

$$\frac{Wu(v-u)}{g} \text{ ft. lbs. per sec.}$$

The energy required to change the momentum in the air stream is the energy added to the system multiplied by the weight of air.

$$\frac{Wv^2}{2g} - \frac{Wu^2}{2g} \text{ ft. lbs. per sec.} = \frac{W(v^2-u^2)}{2g} \text{ ft. lbs. per sec.}$$

$$\text{since efficiency} = \frac{\text{energy output}}{\text{energy input}}$$

$$= \frac{\frac{Wu(v-u)}{g}}{\frac{W(v^2-u^2)}{2g}}$$

$$= \frac{Wu(v-u)}{g} \times \frac{2g}{W(v^2-u^2)} = \frac{Wu(v-u)}{1} \times \frac{2}{W(v^2-u^2)}$$

$$= \frac{2u(v-u)}{v^2-u^2} = \frac{2u(v-u)}{(v+u)\ (v-u)}$$

$$= \frac{2u}{V+u}$$

If the forward speed of the aircraft and the rearward velocity of the jet are equal, then the condition is known as " Unity," and, of course, means that the forward thrust is zero ; but if u is zero, there will be maximum thrust. This explains why efficiency increases with speed of aircraft and altitude.

CHAPTER VII.

THE ROLLS ROYCE DERWENT ENGINES.

As everyone knows, the culminating success of the gas turbine jet-propelled aircraft came with the world air speed record of 606 m.p.h., set up by Sq. Leader Donaldson on November 7th, 1945. This record was established in a Gloucester Meteor with a Derwent V. power unit. This record has since been beaten in America, but by the Donaldson record, following the extraordinary success of previous and less efficient Derwent models (all based on the Whittle patents) in destroying the German V.1. flying bombs, the era of jet propulsion by gas turbine had been established.

The Rolls Royce Derwent V. was designed to fulfil the conditions of an Air Ministry specification, calling for a jet engine for a single-seater interceptor fighter with :

Minimum thrust, 4,000 lbs.
Maximum overall diameter, 55 ins.
Maximum weight, 2,200 lbs.

The Nene was produced to fulfil these conditions and, in fact, far surpassed them with :

Thrust, 5,000 lbs.
Overall diameter, 49½ ins.
Weight, 1,550 lbs.

This was later modified and the Derwent V. was produced.

The characteristics of this unit are as follows :
The axial flow turbine is connected by a shaft to an increased capacity centrifugal compressor. There are nine combustion chambers fed with fuel by high-pressure pumps driven from the unit. Starting ignition is provided by sparking plugs in each of the combustion chambers, and as these are cut out as soon as continuous combustion is effected, they are protected from overheating by screening between the outer casing and the flame tubes, the fuel on starting being sprayed directly

on to the sparking plug. The combustion chambers themselves are connected together by " balance tubes," so that the pressure is equalized, and ignition at starting is facilitated as between one chamber and another. Stopping is effected by operating a fuel cut-off.

Two systems of fuel control are used—1, an aneroid control to vary the fuel pump stroke so as to reduce the flow at high altitudes, and 2, a throttle operated by the pilot.

Cooling and lubrication systems form the ancillary accessories. The characteristic figures are :

Thrust, 4,200 increasing to 5,000 lbs.
Overall diameter, 49 ins.
Weight, 1,500 lbs.
Fuel/Thrust ratio, 1 lb. fuel per lb. thrust per hr.
Revs. per minute, 12,000+

Fuel consumption and thrust :

	Fuel	*Thrust*
1. At sea level	800 gals. per hr.	5,000 lbs.
2. At 10,000 ft.	650 gals. per hr.	4,800 lbs.
3. At 20,000 ft.	500 gals. per hr.	2,800 lbs.
4. At 30,000 ft.	380 gals. per hr.	2,400 lbs.
5. At 40,000 ft.	255 gals. per hr.	1,550 lbs.

THE NENE ENGINE.

From this unit, as has been stated, the Derwent V. was produced. In many respects it has approximately the same efficiency as the scaled-down Derwent, but its dimensions vary slightly as shown above. The Nene has been fitted to the American Shooting Star, which attained speeds in excess of 580 m.p.h., and the De Haviland Vampire.

The light weight and high thrust of the Nene have caused it to be regarded as a serious rival of the conventional piston engine, not only for high speed fighter aircraft but also for the heavy bomber type, for despite its heavy fuel consumption, which would limit its range (using the present tank space of a Lancaster bomber) to 1,000 miles, assuming a total weight of 60,000 lbs. and a cruising speed of 400 m.p.h. at 30,000 ft., the installation of four Nene engines instead of four Merlins

would result in a saving on weight of 4,000 lbs., i.e., 2,000 lbs. each for Nenes instead of 3,000 lbs. each for Merlins, thus leaving a margin of 1,000 each for four additional fuel tanks for increasing the range.

Other combinations of turbine-propeller, piston engine propeller and turbo jet are now being tried, and no doubt in the very near future further sensational progress will be made. Intensive research in all aspects of gas turbines and jet propulsion is in progress at the Ministry of Supply's National Gas Turbine Establishments and at the Power Jet Ltd. Establishments, in which the Government is the chief shareholder.

THE BRISTOL THESEUS I.

A line-drawing of this Propeller-Gas-Turbine power unit, Fig. 12, illustrates a combination which is thought to be advantageous for long-distance flights, where range is more important than the very high speeds at high altitudes, which are a feature of the purely jet-propelled aircraft.

The combination consists of a 9-stage axial flow compressor with a final centrifugal stage, and operating at 300 m.p.h. and at an altitude of 30,000 ft., this produces a compression ratio of 5 : 1 when rotating at 8,200 r.p.m. Power to drive this compressor under the above conditions is 3,500 h.p.

There are eight combustion chambers into which the air, after compression, is received at a pre-heated temperature, so that the combustion chambers are relieved of the task of supplying all the heat. This pre-heating is accompanied by installing a heat exchanger between the compressor and the combustion chambers. Through the outer casings of the heat exchanger the hot combustion gases from the turbine are exhausted, and in their passage they give up to the compressed air passing through the inside ducts a certain amount of the heat which would otherwise be wasted.

Eight combustion chambers fitted radially receive the partially-heated air and, by the combustion of kerosene injected at pressure through the fuel nozzles, raise its temperature to the maximum at the cost of less fuel. Although in the

heat exchanger installation weighs 500 lbs., it is estimated that on long-distance flights it will save its own weight in fuel in a few hours.

Only two combustion chambers are fitted with sparking plugs for initial starting, but all eight are connected by balance tubes to equalize the pressure and combustion.

From the combustion chambers the products of combustion are ducted to 48 tangential nozzles, which direct the high velocity fluid to two independent turbines. The first is used exclusively for supplying power to the compressor, and being on the same shaft its maximum rotating speed is 8,200 r.p.m. This is a two-stage turbine of the Impulse type. The second, a single-stage unit, is used for transmitting the residual energy to the propeller shaft and is connected by a gear train to it. This unit rotates at 900 r.p.m. In effect, the whole power unit can be regarded as a three-stage turbine, but owing to the different functions of the two units, it is perhaps more convenient to draw a distinction.

The dimensions of the unit are favourable for aircraft.

Overall diameter	48 ins.
Length	106 ins.
Weight	2,130 lbs.

Owing to the different efficiencies involved, the output is calculated in EQUIVALENT BRAKE HORSEPOWER, which is defined as

$$\frac{\textit{Propeller Horsepower} + \textit{Jet Horsepower}}{\textit{Propeller efficiency}}$$

On this basis, the equivalent brake horsepower of the British Theseus I. is as follows :

at sea level and 300 m.p.h. = 2,350 E.B.H.P.
at 20,000 ft. ,, ,, ,, = 1,500 E.B.H.P.

Fuel consumption is also calculated on the basis of equivalent brake horsepower, and characteristic values are :

at sea level and 300 m.p.h. = 0.57 lbs. fuel per E.B.H.P. per hr.
at 20,000 ft. ,, ,, ,, = 0.5 lbs. fuel per E.B.H.P. per hr.

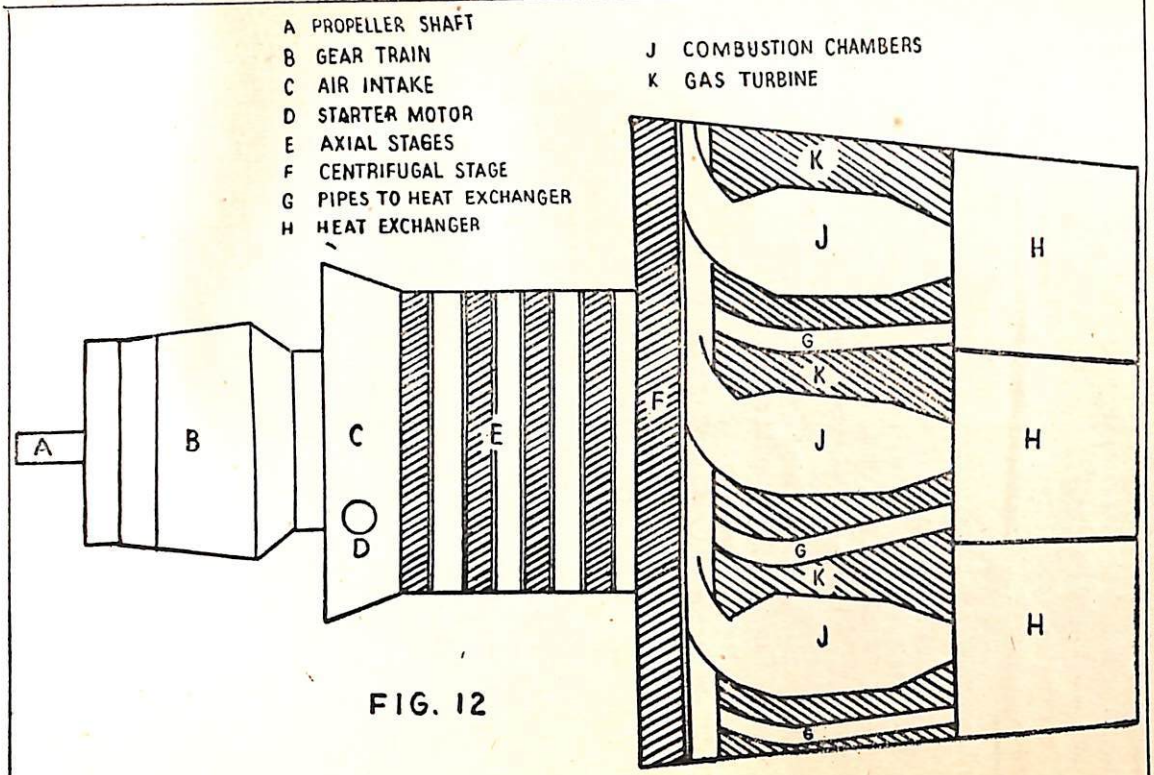

A PROPELLER SHAFT
B GEAR TRAIN
C AIR INTAKE
D STARTER MOTOR
E AXIAL STAGES
F CENTRIFUGAL STAGE
G PIPES TO HEAT EXCHANGER
H HEAT EXCHANGER
J COMBUSTION CHAMBERS
K GAS TURBINE
A
B
C
D
E
F
G
H
J
K

FIG. 12

assuming the fuel to be kerosene, which has calorific value of 10,300 C.H.V. per lb.

Maximum temperature of the fluid at entry into the turbine is regulated to 800°C. by the provision of tappings from the compressor before the compressed air enters the heat exchanger.

This excellent example of the application of the efficiency of different systems for a specific purpose demonstrates the flexibility of turbo-jet and turbine propeller systems, and there can be no doubt that further research into these combinations will produce results if not as sensational, then at least of greater immediate revolutionary value to human progress, than even the control of atomic energy.

APPENDIX.

GLOSSARY.

1. *Single-stage compressors* are those in which the compression from initial to final pressure is completed in a single element.
2. *Multi-stage compressors* are those in which the compression is completed in two or more stages.
3. *Ratio of compression* is the ratio of absolute discharge pressure to absolute inlet pressure either of a compressor as a whole or of any stage of a multi-stage compressor.
4. *Free air* is air at atmospheric pressure and temperature at the place where the compressor is working.
5. *Theoretical Horsepower* is the horsepower required to compress air adiabatically through a specific pressure range. In a multi-stage compressor it is the sum of the horsepower calculated for each stage.
6. *Brake horsepower* is the horsepower calculated by applying a brake to the shaft of a motor. It is the measured horsepower put into a compressor shaft.
7. *Absolute pressure* is the total pressure measured from absolute zero. It is equal to the gauge reading plus barometric pressure on p.s.i.
8. *Absolute temperature* is Degrees Farhenheit plus 460° or Degrees Centigrade plus 273°.
9. *Adiabatic compression* occurs when no heat is transferred to or from the air being compressed.
10. *Isothermal compression* occurs when heat is taken from the air under compression at such a rate that the air temperature remains constant.
11. *Specific heat.* The specific heat of air at constant pressure, C_p, is 0.2375 B.Th.U. per lb.; at constant volume C_v, it is 0.1689. B.Th.U. per lb.
12. *Thrust* is the power exercised for forward propulsion of the reaction due to the expulsion of a rearward jet.
13. *Air constant* $P. = \frac{53.3T}{V}$, $V = \frac{53.3T}{P}$, $T = \frac{PV}{53.3}$
14. *Centrifugal compressor*, see Chapter III.
15. *Axial flow compressor*, see Chapter III.

FORMULAE.

FORCE tends to change the state of rest or motion in a body, e.g., if a man attempts to lift a weight, he will be capable of exercising a limited amount of force. Whether he succeeds or not depends simply on the *amount* of force exercised. So much for stationary objects. But he may also notice that his car has begun to move down an incline, and try to stop it. Here again he will apply force, and whether or not he succeeds in stopping it depends simply on the amount of force applied.

WORK is, so to speak, successful FORCE and is defined as "FORCE," the point of application of which moves in the direction of the force. Hence, if the man lifts the weight he is doing work, and if he stops the car from running in one direction he is doing work, as, at a certain point, if he continues to exert the same force, the car will move in the other direction. So here is a combination of FORCE AND DISTANCE and is calculated by multiplying the force in lbs. by the distance in feet, giving the combined unit of work the ft. lb., e.g., to find the work done in lifting 3 cwts. to a height of 12 ft.:

$$3 \text{ cwts. } (112 \times 3) \times 12 = 4032 \text{ lbs.}$$

POWER. But if the 1 cwt. weight is lifted by a block and tackle it will take longer than if three or four men combined to lift it directly, so now a TIME factor enters into the calculation, and POWER is defined as work divided by time, e.g., to find the POWER required to lift 3 cwts. to a height of 12 ft. by block and tackle in 3 minutes :

$$3 \text{ cwts.} = \frac{(112 \times 3) \times 12}{3} = \frac{4032}{3} = 1344 \text{ ft. lbs./min.}$$

HORSEPOWER. As a standard of calculation for power, the work of which the average London dray horse is capable is taken, and this figure is accepted universally as 33,000 ft. lbs. per min.

EXPANSION. In order to understand the process in a multi-stage turbine, it is well to recapitulate the action of a triple-expansion steam engine. The h.p. of a single cylinder is calculated as :

$$\frac{\text{Area of piston} \times \text{pressure} \times \text{length of stroke} \times \text{No. of strokes per min.}}{33{,}000}$$

Having done its work in the first cylinder, the steam still has some ENERGY left, but obviously the area of the piston must be increased if this energy is to be in equilibrium as to length of stroke and number of revolutions per min. with cylinder No. 1. So although the equation is the same for the second or medium pressure cylinder, the two components, pressure and area of cylinder, must be balanced so as

to maintain the same total pressure throughout:

e.g. Area of piston, 100 sq. ins.
Inlet pressure, 50 lbs. per sq. in. Cylinder No. 1.
Total pressure, 5,000 lbs.

Area of piston, 166⅔ sq. ins.
Inlet pressure, 30 lbs. sq. in. Cylinder No. 2.
Total pressure, 5,000 lbs.

And finally, the same applies to the 3rd. or low-pressure cylinder. Thus the ft. lbs. of work is the same for each cylinder or turbine stage, and hence the work done by the whole unit is the work done by any one cylinder or stage multiplied by the number of cylinders or stages.

FRICTIONAL HORSEPOWER (*F.H.P.*). Any mechanical device experiences losses, chiefly by friction (otherwise perpetual motion would be a simple matter), and these losses are calculated and called FRICTIONAL HORSEPOWER. They are the ideal calculated horsepower, less the output horsepower, known as brake horsepower.

BRAKE HORSEPOWER is the output of a machine measured by applying a load in the form of a brake to the shaft of an engine, and from the last paragraph it will be seen that:

Brake Horsepower = Indicated Horsepower + Frictional Horsepower.

HORSEPOWER HOUR. Again the horsepower can have a time factor, and the amount of power produced by 1 h.p. working for 1 hour will be:

33,000 ft. lbs./min. × 60 min. = 1,980,000 ft. lbs.

HEAT is energy either stored or working. It is calculated by two main units, Centigrade and Fahrenheit. The Centigrade scale shows freezing point as 0 (zero) and boiling point as 100, and Fahrenheit scale shows freezing point as 32° and boiling point as 212°. To convert Fahrenheit to Centigrade:

Subtract 32 from the temperature in F. and multiply the result by $\frac{5}{9}$

$$e.g.,\ 113\ F. = (113-32) \times \frac{5}{9} = \frac{81 \times 5}{9} = 45C.$$

To convert Centigrade to Fahrenheit:

$$e.g.\ 45C. = \frac{45 \times 9}{5} + 32 = \frac{81}{1} + 32 = 113F.$$

SPECIFIC HEAT is the amount of heat required to raise an equal amount of any substance and of water through one degree of temperature and can be shown:

$$\frac{\textit{Heat required to raise 1 lb. of air through } 1°}{\textit{Heat required to raise 1 lb. of water through } 1°}$$

Since water requires more heat than any known liquid, the specific heat of other liquids is a fraction of that of water. The specific heat

of water is calculated in British Thermal Units (B.Th.U.), so the value of the denominator is 1 B.Th.U. for the Fahrenheit scale, or one Centigrade heat unit (C.H.U.) on the Centigrade scale.

JOULE'S EQUIVALENT.

1 B.Th.U. = 778 ft. lbs. of work.
1 C.H.U. = 1,400 ft. lbs. of work.

and the amount of work which can be obtained by complete combustion of a fuel is called its calorific value (C.V. or Cal. V.) expressed in B.Th.U. or C.H.U.

THERMAL EFFICIENCY. This is the ratio between the heat equivalent of the horsepower developed and the heat equivalent of the fuel :

e.g., a turbine uses 1½ lbs. paraffin for producing 1 h.p. hour. (Paraffin C.V. = about 21,000 B.Th.U./lb.) its thermal efficiency per cent. is :

$$\frac{1\ h.p. = 33{,}000\ ft.\ lbs. \times 60\ min.}{1.5\ lbs. \times 21{,}000\ B.Th.U \times 778\ ft.\ lbs.} \times \frac{100}{1} = \frac{1{,}980{,}000}{240{,}070{,}000} \times \frac{100}{1}$$

$$= \frac{198{,}000{,}000}{240{,}070{,}000} = 8.2\%$$

SYMBOLS.

To remove some of the mystery from the mathematical symbols, although for the sake of continuous reading without constant reference these will be repeated as they come up for consideration, it is as well to give them names here and now; many of these are, however, not universally adopted.

B.H.P. = Brake horsepower = 33,000 foot lbs. per minute or 550 foot lbs. per second.

B.Th.U. = British Thermal Unit = the amount of heating or calorific value contained as latent heat, i.e., heat which can be released, contained in fuel. It is the amount of heat which, when released and turned into kinetic heat, will do 778 foot pounds of work. (See Glossary.)

B.H.P.Hr. = British Thermal Units hour = the expenditure of 2546 B.Th.U.

C = Centigrade.
C = Any constant value.
C_p = Specific heat at constant pressure.
C_v = Specific heat at constant volume.
F = Fahrenheit.
F = Force or thrust in lbs.
g = Gravity acceleration = 32.2 feet per second per second.
$H.P.$ = Horsepower.
$hr.$ = hour.
$B.H.P.$ = Brake horsepower.
$I.H.P.$ = Indicated horsepower.
$E.H.P.$ = Equivalent horsepower.
J = Joule's constant = 778 foot lbs./B.Th.U.
P = Absolute pressure.
P_1 = Absolute pressure at inlet of compressor.
P_2 = Absolute pressure at outlet of compressors.
P_3 = Absolute pressure at inlet of turbine.
P_4 = Absolute pressure at outlet of turbine.
Q = Volume flow in cubic feet per minute or second.
R = Gas constant = PV/T in foot lbs./degrees F. (See Chapter II, page 19.)
$r.p.m.$ = Revolutions per minute.
T = Absolute Temperature = in degrees Rankine = degrees Fahrenheit + 460° Fahrenheit.

t = time in seconds or increase in temperature.
t_1 = Inlet temperature to compressor.
t_2 = Outlet temperature from compressor.
t_3 = Inlet temperature to turbine.
t_4 = Outlet temperature from turbine.
U_1 = Velocity of entry air relative to impeller in ft. per sec.
u_1 = Tangential velocity of blade edges at entry, in ft. per sec.
V_1 = Velocity at entry in ft. per sec.
V_2 = Velocity at outlet in ft. per sec.
v = Specific volume in cu. ft. per lb.
W = Weight or weight flow in lbs. per min., sec., or hr.
α = (Greek alpha) = Coefficient of volumetric expansion, and is the same for all gases = $\frac{1}{273}$ of the volume at 0° C. or $\frac{1}{492}$ of the volume at 32°F.
γ = (Greek gamma) = ratio of specific heats.
η = (Greek eta) = Efficiency ratio and may have any subscript.
π = (Greek pi) = 3.1416 or $\frac{22}{7}$.
ρ = (Greek rho) = Density.
σ = (Greek sigma) = Relative density (not used).
Σ = (Greek sigma) = Sum.
ω = (Greek omega) = Rotative speed in radians per sec.
% = Per cent.

A subscript is a small symbol placed below another symbol, e.g., P_1, P_2, C_p.

An index is a small symbol placed above another symbol and indicates that its value is multiplied by itself that number of times, e.g., $V^2 = V \times V$, $P_1^2 = P_1 \times P_1$

$\sqrt{}$ Root = the number which multiplied by itself will give the value of which the root is to be found, e.g., $\sqrt{9} = 3$, or $3\sqrt{27} = 3$.

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GAS TURBINES AND JET PROPULSION

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Ambient air
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